

# Reflectance-based calibration of SeaWiFS.

## II. Conversion to radiance

Robert A. Barnes and Edward F. Zalewski

For instruments that carry onboard solar diffusers to orbit, such as the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), it is possible to convert the instrument's reflectance measurements to radiance measurements by knowledge of the solar irradiance. This process, which generally requires the application of a solar irradiance model, is described. The application of the irradiance model is separate from the measurements by the instrument and from the instrument's reflectance calibration. In addition, SeaWiFS was calibrated twice before launch for radiance response by use of radiance sources with calibrations traceable to the National Institute of Standards and Technology. With the inclusion of the at-launch diffuser-based radiance calibration, SeaWiFS has three possible radiance calibrations for the start of on-orbit operations. The combination of these three into a single calibration requires changes of 4% or less for the current at-launch radiance calibration of the instrument. Finally, this process requires changes of 4% or less for the reflectance calibration coefficients to provide consistency among the radiance calibration, the reflectance calibration, and the solar irradiance. © 2003 Optical Society of America

OCIS codes: 120.0120, 120.0280, 120.5700, 120.5630.

### 1. Introduction

In a companion paper<sup>1</sup> we developed a reflectance-based calibration of the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS). When this calibration is applied, SeaWiFS operates as a reflectometer, viewing the reflected solar flux from both the Earth and the onboard diffuser. Because the Sun is the common source of irradiance for both diffuse reflectors, the ratio of the two SeaWiFS measurements is also the ratio of the two reflectances. The reflectance-based calibration of SeaWiFS allows the direct determination of the remote sensing reflectance of the Earth, relative to the reflectance of the SeaWiFS onboard diffuser. It does not require knowledge of the absolute value of the flux from either the Sun or an integrating sphere in the laboratory. However, the reflectance-based calibration does require the solar flux to be constant during the time between the two measurements in the ratio. In addition, the reflectance-based calibration does not require knowl-

edge of the calibrated radiances for the SeaWiFS measurements because the measurements are applied as a ratio. It is sufficient to know that the instrument output, in digital numbers (DNs), is a linear function of the input radiance, as shown in Barnes *et al.*<sup>2</sup>

Here, that calibration is combined with a solar irradiance model to provide an on-orbit radiance-based calibration for SeaWiFS. Such a calibration is used for other satellite instruments, such as the moderate-resolution imaging spectroradiometer (MODIS)<sup>3</sup> and the Global Imager.<sup>4</sup> For SeaWiFS, this calibration requires knowledge of the absolute value of the solar spectral irradiance at the instrument's input aperture plus knowledge of the reflecting properties of the instrument's diffuser. The reflectance-based calibration of SeaWiFS is summarized in Section 2, the properties of the solar irradiance model used in the conversion to radiance is discussed in Section 3, and the on-orbit radiance calibration is presented in Section 4.

In 1993, at the facility of the instrument manufacturer, Hughes Santa Barbara Research Center (now Raytheon Santa Barbara Remote Sensing), a pre-launch solar radiation-based calibration (SRBC) was performed.<sup>5,6</sup> That calibration duplicates the on-orbit radiance calibration in Section 4, except that it was performed prior to launch and performed at a site below the Earth's atmosphere. The prelaunch SRBC of SeaWiFS is described in Section 5, including

---

R. A. Barnes (rbarnes@seawifs.gsfc.nasa.gov) is with Science Applications International Corporation, Beltsville, Maryland 20705. E. F. Zalewski is with the Optical Science Center, Remote Sensing Group, University of Arizona, Tucson, Arizona 85721.

Received 30 August 2002; revised manuscript received 23 December 2002.

0003-6935/03/091648-13\$15.00/0

© 2003 Optical Society of America

a comparison with the results of the on-orbit radiance calibration in Section 4.

For SeaWiFS, there were two prelaunch laboratory radiance calibrations that used integrating spheres as radiance sources. These calibrations are described in Section 6. In Section 7 these calibrations are combined with the on-orbit calibration from Section 4 to provide revised radiance calibration coefficients for the instrument. The revised coefficients are an unweighted mean of the values from these calibrations. For all eight SeaWiFS bands, the revised coefficients agree with those currently in use at better than the 4% level and fall within the estimated uncertainty ( $k = 1$ ) for the top-of-the-atmosphere radiances from the instrument.

## 2. Reflectance-Based Calibration

In the companion paper<sup>1</sup> we developed the calibration equation for the Earth bidirectional reflectance factor (BRF)  $R_E(t)$  using the SeaWiFS diffuser as an on-orbit reflectance standard. The BRF is defined as the ratio of the radiant flux from a sample surface to that of an ideal diffuse standard surface irradiated in the same way as the sample.<sup>7,8</sup> For an ideal diffuse surface, the bidirectional reflectance distribution function (BRDF)<sup>7,8</sup> has a value of  $1/\pi \text{ sr}^{-1}$ , and its BRF, by definition, is unity (dimensionless). Thus, for an ideal diffuse surface and for other surfaces as well, the conversion constant between BRDF and BRF has a value of  $\pi$  steradians.

For each SeaWiFS band, our calibration equation<sup>1</sup> has the form

$$\begin{aligned} R_E(t) &= \pi F_E(t) \\ &= [\text{DN}(t) - \text{DN}_0(t)]_E \frac{D_{\text{ES}}^2(t)}{\cos(\theta_I)} [\pi k_F(t_0)] \alpha(t_0) \\ &\quad \times [\Delta_G(t)]^{-1} [\Delta_F(t)]^{-1}, \end{aligned} \quad (1)$$

where  $R_E(t)$  is the Earth BRF (dimensionless) at time  $t$  in days after launch. In Eq. (1),  $F_E(t)$  is the Earth BRDF in units of inverse steradians and  $\pi$  is the conversion constant in units of steradians. The term  $[\text{DN}(t) - \text{DN}_0(t)]_E$  gives the DNs measured by SeaWiFS,  $\text{DN}(t)$ , after correction for the instrument's zero offset,  $\text{DN}_0(t)$ . The terms  $D_{\text{ES}}^2(t)$  and  $\cos(\theta_I)$  are corrections for the Earth–Sun distance and the cosine of the solar zenith angle at the time of the measurement, respectively, and both of these corrections are dimensionless. The term  $\cos(\theta_I)$  is a geometric correction for the projection of the incident solar radiation when it is not normal to the Earth's surface. This type of correction applies whenever the illuminated area on a surface overfills the field of view of the instrument measuring the reflected radiation and is not related to the nature of the reflecting surface. It is also possible to provide an Earth reflectance product without this geometric correction, allowing the correction to be applied by the user, as is the case for MODIS.<sup>3</sup>

## 8. Concluding Remarks

The reflectance-based calibration of SeaWiFS<sup>1</sup> provides the basis for a radiance-based calibration of the instrument in the same manner as other sensors that use onboard diffusers as flight standards, such as MODIS<sup>3</sup> and the Global Imager.<sup>4</sup> For each of these instruments, a solar irradiance model is required to obtain the reference radiances for the calibration coefficients. Here, the model of Thuillier *et al.*<sup>20</sup> is preferred. However, the SeaWiFS Project also has two prelaunch laboratory calibrations of the instrument. One of them, the 1997 prelaunch calibration,<sup>26</sup> provides the current (July 2002 reprocessing) calibration coefficients, and those coefficients have not changed from the launch of SeaWiFS in August 1997 to the current reprocessing of the data set.

A revised at-launch calibration for SeaWiFS is proposed here, based on an unweighted average of the three instrument calibrations now in existence. The revised coefficients are listed in Table 9. They agree with the current values to within the estimated uncertainty ( $k = 1$ ) for the SeaWiFS top-of-the-atmosphere radiances. The differences range from 1.2% (revised coefficient higher) for SeaWiFS band 1 to 3.5% (revised coefficient lower) for SeaWiFS band 7. The differences are shown in Fig. 5(a).

The creation of the revised SeaWiFS radiance-based calibration coefficients has an impact on the reflectance-based coefficients for the instrument because the radiance and reflectance calibrations are connected by the solar irradiance, as shown in Eq. (8). This connection is applied in Table 9, where the revised radiance calibration coefficients  $k_{L*}(t_0)$  are combined with the band-averaged solar irradiances from Thuillier *et al.*<sup>20</sup> to calculate the revised reflectance coefficients for SeaWiFS,  $k_{F*}(t_0)$ . This step is necessary to provide a consistency in the radiance and reflectance calibrations of the instrument. Overall, the revised reflectance-based calibration coefficients  $k_{F*}(t_0)$  are larger than the corresponding coefficients from Ref. 1. However, they differ by less than the uncertainty for the measured top-of-the-atmosphere reflectances, which is estimated to be between 4 and 5% ( $k = 1$ ).<sup>1</sup> The increases in the reflectance calibration coefficients are 0.2, 0.7, 2.3, 2.3, 3.0, 3.7, 4.1, and 2.7% for bands 1–8, respectively. They propagate directly into revised values for the instrument's at-launch diffuser BRDFs.